Final Report

Design and Processing of Shape Memory Polymer (SMP)/Shape Memory Alloy (SMA) Composites

Contractor (PI): Hirohisa Tamagawa

WORK Information:
Organization Name: Gifu University
Organization Address: 1-1, Yanagido, Gifu
Postal Code: 501-1193
Country: Japan
Work Phone Number: +81-58-293-2529
Work Fax Number: +81-58-230-1893
Work Email Address: tmgwhrhs@gifu-u.ac.jp

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14. ABSTRACT
This research was has been conducted primarily to create a thermo-responsive two-way shape change polymer. Such a material could work as a thermo-responsive actuator, a thermo-responsive valve, a thermo-responsive switch in broad range of engineering field. Two-way shape change materials such as a shape memory alloy (SMA) and a piezoelectric are been already available on the market. However, the existing thermo-responsive two-way shape change materials still has a large room to be improved. Most of them are primarily made from metal and/or ceramics and not from polymer. Polymer has its own intrinsic natures that neither metal nor ceramics has, for example, largely deformity, low mass, electrically insulating. Shape memory polymer (SMP) is made from polymer as its name suggests and it changes its shape by the temperature increase. But cooling the SMP does not restore its shape back to the original shape. It is merely a one-way shape change not two-way. In addition to that, SMP softens significantly in the heated state. Hence, SMP cannot serve as a practical thermo-responsive actuator or so. It can be utilized only for limited engineering purposes. To the best knowledge, there are no practical thermo-responsive two-way shape change polymers. Therefore, creating a thermo-responsive two-way shape change polymer has a significant meaning. The thermo-responsive two-way shape change polymer could broaden usefulness of two-way shape change materials including metal and/or ceramics-based ones. Some successful results were obtained and are reported.

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Motive:

This research was has been conducted primarily for creating a thermo-responsive two-way shape change polymer. Such a material could work as a thermo-responsive actuator, a thermo-responsive valve, a thermo-responsive switch and etc in broad range of engineering field.

Nowadays two-way shape change materials such as a shape memory alloy (SMA) and a piezoelectric have been already available on the market. However, the existing thermo-responsive two-way shape change materials still has a large room to be improved. Most of them are primarily made from metal and/or ceramics not made from polymer. Polymer has its own intrinsic natures that neither metal nor ceramics has, for example, largely deformity, low mass, electrically insulating. Shape memory polymer (SMP) is made from polymer as its name suggests and it changes its shape by the temperature increase [1]. But cooling the SMP does not restore its shape back to the original shape. It is merely one-way shape change not two-way shape change. In addition to that, SMP softens significantly in the heated state. Hence, SMP cannot serve as a practical thermo-responsive actuator or so. It can be utilized only for limited engineering purposes. To the best knowledge, there are no practical thermo-responsive two-way shape change polymers. Therefore, creating a thermo-responsive two-way shape change polymer has a significant meaning. The thermo-responsive two-way shape change polymer could broaden usefulness of two-way shape change materials including metal and/or ceramics-based ones. Some successful results were obtained and are reported.

Research outcomes:

As a first step toward the research goal, I tried to fabricate a thermo-responsive two-way shape change composite consisting of metal and polymer. It resulted in a relatively successful outcome, and it is described in the former section, Section A. As a second step, laminate shape thermo-responsive two-way shape change all-polymeric materials were fabricated, and it is described in the latter section, Section B. The section B is further divided into two parts B-a and B-b. The section B-a describes the successful outcome of creating a thermo-responsive two-way shape change all-polymeric laminate. The section B-b describes the improvement of the all-polymeric laminate properties.

A. Thermo-responsive two-way shape change composite

A thermo-responsive two-way shape change composite was fabricated. It consisted of three components, SMA wires, an elastic polymer plate (hereafter called EP plate for short) and a SMP plate.

A-1. Characteristics of individual components

The SMA wire used is Biometal (Toki Corp., Japan). It is a fine wire whose diameter is around 100 μm, and it exhibits contract above 70 ºC, while it elongates below 70 ºC. The length change is induced immediately in response to temperature change. The EP plate is merely an elastic polymer plate. Its elastic property maintains unchanged from room temperature to 80 ºC. The SMP plate used is a polyurethane plate. It exhibits shape memory effect around at glass transition temperature, Tg , 20 ºC.

A-2 Characteristics of composites

A thermo-responsive two-way shape change SMA-EP-SMP composite was successfully fabricated. But, before showing its characteristics, the characteristics of SMA-EP composite are explained for the purpose of better understanding of SMA-EP-SMP composite.

A-2.1 SMA-EP composite

Figure 1 shows the structure of SMA-EP composite. A SMA wire is tied to the both ends of the EP plate. Once the SMA-EP composite is heated above 70 ºC, the SMA wire contracts and the EP plate deforms as illustrated in Fig. 2. Entire length of the SMA-EP composite, L_h, is less than its original length, L_o. Cooling the SMA-EPP composite causes elongation of the SMA wire, and the SMA-EP composite shape gets back to its original straight shape because of the elastic nature of EP. This process is thermo-reversible two-way shape change. Figure 3 shows the deformation of actual SMA-EP composite induced by environmental temperature change. The SMA-EP composite took on straight shape at the room temperature, while it took on deformed shape at 70 ºC, where heating was realized by submerging the SMA-EP composite in a hot water and cooling was achieved merely by taking it out of the hot water. The actual SMA-EP composite exhibited deformation expected. It is the thermo-responsive two-way shape change, and it appears to fulfill the research objective. However, there are some drawbacks about the SMA-EP composite. Once the heating is stopped, the shape gets back to the original straight shape. Heat energy consumption is demanded for retaining the deformed shape. It is a significantly undesired property for its practical use. Furthermore, it is almost impossible to achieve the intermediate shape (moderately deformed state, see Fig. 4) as a stable state. Only the two states, the straight shape state and the fully deformed shape state, are achievable as stable states. For the purpose of overcoming those

drawbacks, a SMA-EP-SMP composite was fabricated as next.

A-2.2 SMA-EP-SMP composite

A SMA-EP-SMP composite was fabricated by attaching a SMP plate to the bottom of the SMA-EP as illustrated in Fig. 5. The SMP plate used is a polyurethane plate. It softens above 30 ºC, while it is mechanically in the hard state at the room temperature below 30ºC. Such a mechanical strength change of SMP plate is reversible process in accordance with the environmental temperature. It also exhibits shape memory effect at 30 ºC, but it is one-way shape change, irreversible process.

Now, the characteristics of the SMA-EP-SMP composite are described. The SMA-EP-SMP composite is in the straight shape state below 70 ºC as illustrated in Fig. 6. The raise of temperature above 70 ºC causes its deformation, since the SMP plate is in the softened state and the SMP wire contracts. Cooling the temperature below 70 ºC but above 30 ºC brings the SMA-EP-SMP composite in the deformed state back to the original straight shape state, since the SMP plate is still in the softened state and the SMA wire elongates and especially due to the elastic nature of EP plate.

Rapid cooling of the SMA-EP-SMP composite below 30 ºC, during its shape recovery process, causes shape fixation of the SMP component due to its hardening. It eventually results in the shape fixation of entire SMA-EP-SMP composite, which is in intermediate state of deformation, as it is in a stable state as illustrated in Fig. 6. Figure 7 shows the experimental observation of SMA-EP-SMP composite shape change process. Although actual deformation in Fig. 7 is not as large as that in the illustration of Fig. 6, it is possible to see that the SMA-EP-SMP composite exhibits the deformation as expected by carefully seeing its tip displacement shown in Fig. 7.

One might raise a question, why the EP plate is needed for fabricating a thermo-responsive two-way shape change composite. He might say that the SMA-SMP composite can exhibit thermo-responsive two-way shape change, though it does not have an EP component. Think about the SMA-SMP which is in the straight shape originally at the room temperature as illustrated in Fig. 8. Once it is heated above 70 ºC, it deforms due to softening of the SMP plate and contract of the SMA wire. Once it is cooled down below 70 ºC but above 30 ºC, its shape gets back to its original straight shape due to the elongation of SMA wire and the shape memory effect – tendency of shape recovery – of the SMP plate. Rapid cooling in the middle of such shape recovery process even results in shape fixation of its intermediate state of deformation because of hardening of the SMP component. Therefore, it is quite natural that he raises such a question, "why is the EP plate needed for fabricating a thermo-responsive two-way shape change composite ?". However, the EP plate plays a quite important role for the SMA-EP-SMP composite. The shape change of the SMA-SMP composite is always induced above 30 ºC, since the SMP plate should be in the softened state, otherwise, it is quite difficult to induce the shape change of the SMA-SMP composite due to the tough mechanical strength of SMP plate below 30 ºC. But the SMP in the soft state at or above 30 ºC is quite susceptible external force. Therefore the SMA-SMP composite is easily deformed into undesired shape even by quite small external force. It is a serious drawback. The EP plate is elastic at the broad range of temperature. It does not lose its mechanical strength as well as elastic property. Therefore, the EP plate needs to be used. The SMA-EPP-SMP composite can endure undesired external force owing to the EP plate.

Before closing this section, the temperature vs. deformation diagram of SMA-EP-SMP composite is shown in Fig. 9 for the purpose of easy understanding of the SMA-EP-SMP composite characteristics.

B. Thermo-responsive two-way shape change polymeric laminate

Two kinds of thermo-responsive two-way shape change all-polymeric laminates were fabricated [2,3]. One consisted of an epoxy plate and a carbon fiber reinforced plastic (CFRP) plate [2]. The other one consisted of a polyvinylchloride (PVC) plate and a CFRP plate [3]. The section B-a describes the properties of the CFRP-Epoxy laminate. The section B-b describes the properties of CFRP-PVC laminate. Since the CFRP-PVC laminate had better properties than the CFRP-Epoxy laminate, the further investigation of the CFRP-PVC laminate was carried out experimentally and theoretically in detail.

B-a CFRP-Epoxy laminate

A SMA-EP-SMP thermo-responsive two-way shape change composite was successfully fabricated as described in the section A. That work was carried forward. I tried to fabricate a thermo-responsive two-way shape change all-polymeric laminate, which has EP-SMP structure.

B-a-1 Characteristics of individual components

An all-polymeric laminate was fabricated by attaching a SMP plate of epoxy to an EP plate of CFRP plate with instant glue. The epoxy plate has a unique property of exhibiting shape memory effect around at 50 ºC, and the CFRP plate has quite high elasticity and quite low coefficient of thermal expansion (they are detailed in the section B-b). Dimensions of epoxy plate were 80 mm in length × 7 mm in width × 3 mm in thickness and those of CFRP was 80 mm in length × 12 mm in width × 0.5 mm in thickness. Figure 10 shows the resultant CFRP-Epoxy laminate fabricated.

B-a-2 Characteristics of Epoxy-CFRP laminate

B-a-2.1 Deflection of laminate

The CFRP-Epoxy laminate was horizontally clamped in the 25 ºC environment as shown in Fig. 11 (a). Once it was heated to 80 ºC by a hair-dryer, it bent as shown in Fig. 11 (b) within a few minutes. Its bending curvature was 0.002 mm^{-1}. Once the heating was stopped, the CFRP-Epoxy laminate temperature gradually decreased to room temperature, and its shape got back to the straight shapes shown in Fig. 11 (c) in a few minutes.

Induction of the CFRP-Epoxy laminates bending is due to the difference of coefficients of thermal expansion between the epoxy and CFRP plates. The CFRP-Epoxy laminate took on two shapes as stable shapes as shown in Fig. 11 (b) and (c) at 80 and 25 ºC, respectively. Moreover, it could take on intermediate state as a stable shape by employing rapid cooling technique. One of components of the CFRP-Epoxy laminate was an epoxy plate. Therefore, if the CFRP-Epoxy laminate is rapidly cooled down to far below its glass transition temperature in the middle of its shape change from the bent state shown in Fig. 11 (b) to the straight state shown in Fig. 11 (c), the intermediate deformed shape is fixed as a stable state.

B-a-2.2 Shape recovery under load

It was investigated if deflection of the CFRP-Epoxy laminate under a load would be induced by heating-cooling thermal cycling. One end of CFRP-Epoxy laminate was clamped and its entire body was horizontally fixed as shown in Fig. 12 (i). Load was applied by placing six coins, totally 28 g, on the other end of

laminate at 25 ºC as shown in Fig. 12 (ii).

The laminate was not deformed at all at 25 ºC even under the load as shown in Fig. 12 (ii). Heating the laminate at 80 ºC for two minutes caused its deflection as shown in Fig. 12 (iii) because of the thermal expansion of epoxy plate and the load. Stopping to heat it up resulted in its shape recovery as shown in Fig. 12 (iv). As a matter of fact, bending mechanism of the CFRP-Epoxy laminate is basically same as that of well-known old-fashioned actuator, that is, bimorph actuator. Fabrication of a thermo-responsive two-way shape change polymeric material is unexpectedly easily achieved by the old-fashioned technique. The CFRP-Epoxy laminate exhibited fairly good performance in terms of deflection and force bearing. Therefore, it possesses quite high potential to be utilized as a practical all-polymeric actuator or so.

B-b CFRP-PVC laminate

The CFRP-Epoxy laminate is an all-polymeric laminate and has the EP-SMP structure. It exhibited the two-way shape change in response to the environmental temperature. But its deflection speed was slow. Hence, next task was fabrication of a fast-responsive all-polymeric laminate. An EP-EP structure polymeric laminate was fabricated. One EP was a polyvinylchloride (PVC) plate and another EP was a CFRP plate. The resultant CFRP-PVC laminate exhibited fast deflection. Properties other than deflection speed were also quite fascinating. Those properties were investigated experimentally and theoretically in detail.

B-b-1 Fabrication of a CFRP-PVC laminate

A thermo-responsive two-way shape change polymeric laminate made from an EP of PVC plate (7 cm in length × 1 cm in width × 0.41 mm in thickness) and an EP of CFRP plate (7 cm in length × 1 cm in width × 0.50 mm in thickness) was fabricated. The PVC plate was attached to the CFRP plate with an instant glue (CC-33A; Kyowa Electronic Instruments Co., Ltd. Tokyo), resulting in a CFRP-PVC laminate.

The shape of the CFRP-PVC laminate at room temperature (300 K) immediately after its fabrication was straight. However, it took on a permanently deflected shape toward the PVC plate direction at 300 K but was straight at 340 K after it had undergone several initial thermal cycles at 300 K ↔ 340 K, as shown in Fig. 13. The dotted horizontal line in Fig. 13 (a) represents the straight line. The cause of such a phenomenon is discussed later on

B-b-2 Deflection of CFRP-PVC laminate under thermal cycling

Figure 14 shows the experimental setup for measuring temperature dependence of CFRP-PVC laminate deflection. The CFRP-PVC laminate was suspended in water bath, the temperature of which was repeatedly raised and cooled between 300 K and 340 K in order to control the CFRP-PVC laminate temperature. Horizontal displacement of CFRP-PVC laminate 6 cm away from the clamping point was measured by a laser displacement sensor, and the displacement was converted into curvature. Figure 15 shows the temperature dependence of CFRP-PVC laminate curvature by the two thermal cycle. Behavior of temperature vs. curvature of CFRP-PVC laminate is merely a straight line and shows no hysteresis. Such a simple behavior is quite preferable for the practical use of CFRP-PVC laminate such as an actuator and etc.

B-b-3 Deflection of CFRP-PVC laminate under a load

One end of CFRP-PVC laminate was horizontally clamped in the air at 300 K, and four coins (totally 28 g = 274 mN) were placed on the other end of CFRP-PVC laminate as shown in Fig. 16 (a). Once the CFRP-PVC laminate was heated up to 340 K, it straightened as shown in Fig. 16 (b) within several seconds. It was quite fast deflection. Within 30 s of cooling down naturally, the CFRP-PVC took the shape shown in Fig. 16 (c), which was almost the same as its original shape, shown in Fig. 16 (a). It was relatively fast motion. The CFRP-PVC laminate exhibited fast motion and reversible shape change even under a load in air. In practical terms, these are quite important properties.

B-b-4 Thermal strain of CFRP-PVC laminate component under thermal cycle

Figure 17 (a) shows the temperature dependence of PVC plate thermal strain for one thermal cycling 300 K → 340 K → 300 K. Fine and fat lines in the diagram show the strains in the in-plane directions which are orthogonal to each other. There are no differences between them, which shows that PVC in-plane structure is isotropic. Figure 17 (b) shows the temperature dependence of CFRP plate strain for one thermal cycle, too, where fine and fat lines show the strains in the in-plane directions which are orthogonal to each other. Inset is the magnified diagram of temperature vs. CFRP strain. CFRP in-plane structure is isotropic, too. Compared with the PVC plate, the in-plane thermal strain of CFRP plate changed less against temperature change and was maintained at almost constant level irrespective of temperature. The significant difference between the in-plane thermal strains of PVC and CFRP is caused the CFRP-PVC laminate bending. These results show that the efficient deflection of CFRP-PVC laminate is bought about by the significant difference in strain between PVC and CFRP plates.

B-b-5 Tensile tests & DSC measurement

Tensile tests of PVC and CFRP plates were carried out at nine different constant temperatures between 295 K and 339 K. Figure 18 (a) shows four of the nine stress-strain curves obtained. The rest of stress-strain curves were all obtained at the temperature not over 323 K, and they fall roughly on the stress-strain curve of 323 K shown in Fig. 18 (a). Therefore, the mechanical stiffness of PVC at no higher than 323 K is almost same one another. However, mechanical stiffness of a PVC plate weakens gradually as the temperature rose beyond 323 K as clearly seen in Fig. 18 (a). It was speculated that it was due to the existence of glass transition temperature, Tg, a bit above 323 K. Figure 19 shows the DSC chart of 1 mg of PVC and 1 mg CFRP, and there is an onset point of Tg for PVC at 335 K, which is quite close to the Tg suggested by the tensile tests.

All nine stress-strain curves of CFRP plate fall on almost the same line (Fig. 18 (b) shows three of them.). Hence, it is concluded that CFRP plate mechanical stiffness is indifferent to the temperature. In fact, Fig. 19 suggests that CFRP does not have Tg in the focused temperature region unlike PVC.

B-b-6 Theoretical analysis of deflection and force generated

B-b-6.1 Bending curvature

The CFRP-PVC laminate was fabricated at 298 K by gluing straight shape PVC and CFRP plates together. As described in the section B-b-1, the shape of CFRP-PVC was initially straight at 300 K. However, its deflection behavior settled down, taking on a deflected shape at 300 K and a straight shape 340 K, as shown in Fig. 13, after it underwent the 300 K ↔ 340 K a few initial thermal cycles. The occurrence of CFRP-PVC laminate

deflection at 300 K after the initial thermal cycle was likely due to the compression force exerted on PVC plate of the CFRP-PVC laminate in the middle of the initial thermal cycling treatment. Interface between the PVC plate and the CFRP plate of the CFRP-PVC laminate was completely attached with glue. Once the temperature of the CFRP-PVC laminate had been raised to 340 K in the initial thermal cycling, the PVC plate tended to expand as shown in Fig. 17 (a), while the CFRP plate tended to maintain its original shape as shown in Fig. 17 (b). The PVC plate cannot change its shapes so freely in accordance with the environmental temperature because its deflection was is strongly restricted due to its strong adhesion to the CFRP plate which had quite small coefficient of thermal expansion. Such a strain disparity between the PVC and the CFRP plates induced compression force to the PVC plate at 340 K as illustrated in Fig. 20. Molecular chain of PVC plate was able to move fairly freely at 340 K, since the Tg of PVC plate was a slightly below 340 K. Hence, the release of motion restriction of PVC molecular chain and the induction of compression force to PVC plate could cause rearrangement of the PVC molecular chain orientation, resulting in the anisotropic molecular structure of PVC plate. Consequently, the deflection property change of the CFRP-PVC was induced after the initial thermal cycling treatment.

Bearing in mind the deflection property change of the CFRP-PVC laminate by the initial thermal cycling, a theoretical analysis of the CFRP-PVC laminate deflection was carried out. Simultaneous equations represented by the following equations (1) ~ (5) are derived about the arbitrary cross section of the CFRP-PVC laminate, where coordinate system is set to the CFRP-PVC laminate as illustrated in Fig. 21.

The balance of axial forces, where N_i (i = U, I, L) represents internal forces exerted on the neutral axis of PVC plate, the glue layer and the CFRP plate, respectively, is shown by the following equations:

$$N_U + N_I + N_L = 0 \tag{1}$$

The balance of moments, M_i (i = U, I, L) represents the internal moments exerted on the PVC plate, the glue layer and the CFRP plate, respectively, t_i represents the thickness of those layers, respectively, and b and m represent the width of CFRP-PVC and the internal moment per unit width induced by external load, respectively.

$$M_U + M_I + M_L - N_U \frac{(t_U + t_I)}{2} + N_L \frac{(t_L + t_I)}{2} = m \cdot b \tag{2}$$

Matching of the curvatures of all layers, where Θ represents the CFRP-PVC curvature, E_i (i = U, I, L) represents Young's moduli of the PVC plate, the glue layer and the CFRP plate, respectively, and I_i (i = U, I, L) represents their geometric moments of inertia, respectively.

$$\Theta \equiv \frac{M_U}{E_U I_U} = \frac{M_I}{E_I I_I} = \frac{M_L}{E_L I_L} \tag{3}$$

Matching of axial strains at all the interfaces,

$$\frac{\Theta t_U}{2} + \frac{N_U}{E_U A_U} + \alpha_U \Delta T + e_o = -\frac{\Theta t_I}{2} + \frac{N_I}{E_I A_I} + \alpha_I \Delta T \tag{4}$$

$$\frac{\Theta t_I}{2} + \frac{N_I}{E_I A_I} + \alpha_U \Delta T = -\frac{\Theta t_L}{2} + \frac{N_L}{E_L A_L} + \alpha_L \Delta T \tag{5}$$

where A_i (i = U, I, L) represents sectional areas of the PVC plate, the glue layer and the CFRP plate, respectively,

α_i (i = U, I, L) represents their coefficients of thermal expansion, respectively, and ΔT represents the environmental temperature in reference to the room temperature, that is, $\Delta T = T - 298$. e_o is the strain of PVC plate at 298 K, which was induced by the initial thermal cycle applied to the CFRP-PVC laminate.

The CFRP-PVC laminate bending stiffness per width is represented by eq (6), where $h = t_U + t_I + t_L$, $k_U = E_U(T)t_U$, $k_I = E_I(T)t_I$, $k_L = E_L(T)t_L$.

$$k_{bend} = \frac{k_U t_U^2 + k_L t_L^2 + k_I t_I^2}{12} + \frac{k_U k_L (h + t_I)^2 + k_U k_I (h - t_L)^2 + k_L k_I (h - t_U)^2}{4(k_U + k_L + k_I)} \tag{6}$$

The above simultaneous equations (1) ~ (5) are solved with respect to M_i and N_i. Consequently, Θ is obtained by the equation (7) by employing those M_i and N_i.

$$\Theta = \frac{1}{k_{bend}} \left[m + \left\{ c_U (\alpha_U \Delta T + e_o) + c_L \alpha_L \Delta T + c_I \alpha_I \Delta T \right\} \right] \tag{7}$$

where

$$c_U = -\frac{k_L (h + t_I) + k_I (h - t_L)}{2(k_U + k_L + k_I)} k_U$$

$$c_L = \frac{k_U (h + t_I) + k_I (h - t_U)}{2(k_U + k_L + k_I)} k_L$$

$$c_I = \frac{k_U (h - t_L) - k_L (h - t_U)}{2(k_U + k_L + k_I)} k_I$$

Θ is calculate as a function of ΔT. Before carrying out the calculation, it is necessary to determine E_U, E_L, E_I, t_U, t_L, t_I, α_U, α_L and α_I. t_U, t_I and t_L are 0.41 mm, .09 mm and 0.50 mm, respectively, as measured with the micrometer. α_U and α_L are given as slopes of curves shown in Figs. 17 (a) and (b), respectively. E_L is given by a slope of the CFRP stress-strain curve (three of the nine curves are shown in Fig. 18 (b)). All nine CFRP stress-strain curves have almost same slope. E_L is regarded as constant regardless of temperature. Therefore, we obtained E_L simply averaging all the nine curve slopes. Figure 18 (a) indicates that E_U is temperature dependent. Therefore, slope of each stress-strain curve, which was measured at nine different temperatures, was obtained. E_U is shown in Fig. 22 with a trend line. The actual Young's modulus of PVC plate of CFRP-PVC laminate must be different from the E_U shown in Fig. 22, since the rearrangement of molecular structure of PVC plate is induced by the initial thermal cycling of CFRP-PVC laminate as described earlier. Assuming that the actual Young's modulus of PVC plate is not so very different from Young's modulus shown in Fig. 22. Hence, we take the Young's modulus shown in Fig. 22 as E_U. Although Young's modulus has stepwise change around at 325 K as clearly indicated by the trend line in Fig. 22, the amount of change is not so significant. Therefore, we approximate E_U by the equation (8) derived by the regression analysis.

$$E_U = -0.044 \times 10^9 \Delta T + 3.132 \times 10^9 \tag{8}$$

Other data used for the curvature calculation is summarized in Table 1. Figure 23 shows the theoretical and experimental results of ΔT vs. Θ under the condition of m = 0 (zero load). Concerning the theoretical result in Fig.

22, e_o was determined so that Θ theoretically obtained at 298 K would agree with the Θ experimentally obtained at 298 K. Experimental result in Fig. 23 was obtained by rearranging the data in Fig. 15, so the curvature at 298 K can be considered as a reference. Theoretically obtained curvature reproduces well the experimentally obtained curvature. Hence the above equations and concept are all valid for explaining the bending behavior of CFRP-PVC laminate.

B-b-6.2 Temperature-Deflection-Force

Large deflection of CFRP-PVC laminate under large load is a quite important performance. In this section, efficiency of CFRP-PVC laminate deflection is theoretically investigated in terms of tip displacement of CFRP-PVC laminate, δ, under the load, P, in accordance with the temperature, T.

δ is derived by solving equation (9) under the boundary conditions given by equations (10-1) and (10-2), resulting in equation (11).

$$\frac{d^2w}{dx^2} = \Theta \tag{9}$$

$$\left.\frac{dw}{dx}\right|_{x=0} = 0 \tag{10-1}$$

$$\left.w\right|_{x=0} = 0 \tag{10-2}$$

where x = 0 is clamping point of CFRP-PVC laminate.

$$\left.\delta\right|_{x=0} = \frac{1}{k_{bend}}\left(\frac{P\ell^3}{3b} + \left\{c_U\left(\alpha_U\Delta T + e_o\right) + c_L\alpha_L\Delta T + c_I\alpha_I\Delta T\right\}\frac{\ell^2}{2}\right) \tag{11}$$

where ℓ is the length of CFRP-PVC laminate, x = ℓ represents the coordinate of CFRP-PVC laminate tip on which a load P is placed and m is given by equation (12).

$$m = \frac{P(\ell - x)}{b} \tag{12}$$

Figure 24 shows the T – δ – P plane obtained by equation (11), where the specimen dimensions for this computation was same that of CFRP-PVC laminate. In order to assess the validity of the computational result shown in Fig. 24, the amount of maximal CFRP-PVC laminate tip displacement under a downward load of 230 mN by the change of environmental temperature from 300 K to 340 K was experimentally measured. The amount of maximal tip displacement experimentally measured was 4.6 mm, and the theoretical obtained tip displacement was 4.6 mm, too. Hence the theoretical result shown in Fig. 24 must predict the actual T – δ – P relationship of CFRP-PVC laminate quite well. Based on the theoretical prediction, the amount of maximal tip displacement of CFRP-PVC laminate reaches quite large as large as 6.8 mm even under the tip load P = -300 mN (300 mN downward load).

Conclusions:

Research conclusions about the thermo-responsive two-way shape change composite and the thermo-responsive two-way shape change polymeric laminate are described below.

A thermo-responsive two-way shape change composite consists of three components, SMA wires, an EP plate and a SMP plate was successfully fabricated. It is a SMA-EP-SMP composite. Based on the successful fabrication of the SMA-EP-SMP composite, I tried to fabricate a thermo-responsive two-way shape change all-polymeric laminate. It is an EP-SMP laminate consisting of an EP of CFRP and a SMP of epoxy. It exhibited even larger deflection than the deflection of SMA-EP-SMP composite. The investigation of EP-SMP laminate was further extended to the fabrication of an EP-EP laminate using an EP of CFRP and an EP of PVC. It exhibited deflection comparable to or more than the deflection of EP-SMP laminate, and its deflection speed was even faster than that of the EP-SMP laminate. Theoretical analysis was carried out and the results obtained were verified experimentally. It turned out that theory predicted the deflection behavior of the EP-EP laminate under a load in accordance with temperature quite well. Also the theory predicted that the EP-EP laminate can exhibit fairly large tip displacement even under a relatively heavy load.

Publications:

Proceeding (refereed)

1. “Alteration of Thermal Characteristics of Polymer for the Purpose of Creating a Two-stage Shape Memory Polymer”, H. Tamagawa, Fusem 2009, Bangkok (2010).

Refereed journal

2. “Thermo-responsive two-way shape changeable polymeric laminate”, H. Tamagawa, Materials Letters, 64, 749-751, (2010).

3. “Mechanical characteristics of a thermo-responsive two-way shape change polymeric laminate”, H. Tamagawa, K. Kikuchi and G. Nagai, accepted in Sensors & Actuators: A. Physical, In Press (2010).